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Micro-scale multi-effect distillation system for low steam inputs

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Abstract

Distillation can remove all types of contaminants at any concentration level. In this phase change method the feed water is evaporated into steam using a heat source. The vapor formed leaves behind all contaminants in the feed water. The steam led to a condenser gives premium quality water with Total Dissolve Solids (TDS) less than 10 ppm. Generation of 1 kg of steam takes about 1kWh of energy making it energy and cost intensive. Recycling of latent heat of vaporization by Multi-Effect Distillation (MED) makes the process economical. The challenge is to develop small scale MED units for applications in rural areas. The paper describes a Micro Scale MED (MSMED) designed specifically for a low heat source where amount of steam generated is low as with small solar energy collectors. An earlier MED design by some of the present authors, comprising vertical tube evaporators, condenser and water reservoir was optimized for MSMED to work with about 3 kg input of steam at 1.5 bar, which can be generated by a solar concentrator of area 6 m^2. Using 3 effects and a condenser the MSMED was able to produce 11 to 12 liters of water per hour. The Gained Output Ratio (GOR) was 3.6 and the heat recovery at every effect was high. The TDS of the distilled water was reduced from an initial value of 748 to less than 10 ppm..

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Keywords: Multi-effect distillation; recycling latent heat; total dissolved solids; drinking water preparation.

Nomenclature

A	area of cross section of heat transfer
D	water flow rate
H_{fg}	latent heat of vaporization
M_d	rate of condensation
U	overall heat transfer coefficient
ΔT	temperature difference

1. Introduction

High level of water pollution due to industrial activities, growth of population and increasing requirement of water for the agricultural sector has led to rampant pollution of water sources. In many areas natural salinity of water is the issue. Distillation can remove all types of contaminants at any concentration level. In this phase change method the feed water is evaporated into steam using a heat source. The vapors so formed leave behind all contaminants in the feed water. Condensation of these vapors gives premium quality water, with total dissolved solids (TDS) as low as 10 parts per million (ppm). Energy required for distillation is independent of concentration level of impurities in feed water. The major drawback with the distillation process is the high initial energy input. It takes about 1 kWh of energy to produce 1 kg of

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steam or equivalent amount of distilled water. Recycling of latent heat of vaporization several times, as in multi effect distillation, makes the process more economical. The efficiency of heat recycling in distillation is expressed in terms of the Gained Output Ratio (GOR).

In our earlier work a Small scale MED (SMED) was designed with vertical tube evaporators to handle 30 Kg/hr of steam generated by a boiler. If steam is produced using solar energy, expenditure on fuel can be saved. Considering that a Fresnel mirror collector of 6 m^2 can give about 3 kg/hr of steam, a Micro Scale MED (MSMED) was designed for working at this level of steam output. In this paper the fabrication and parametric studies on this system are presented.

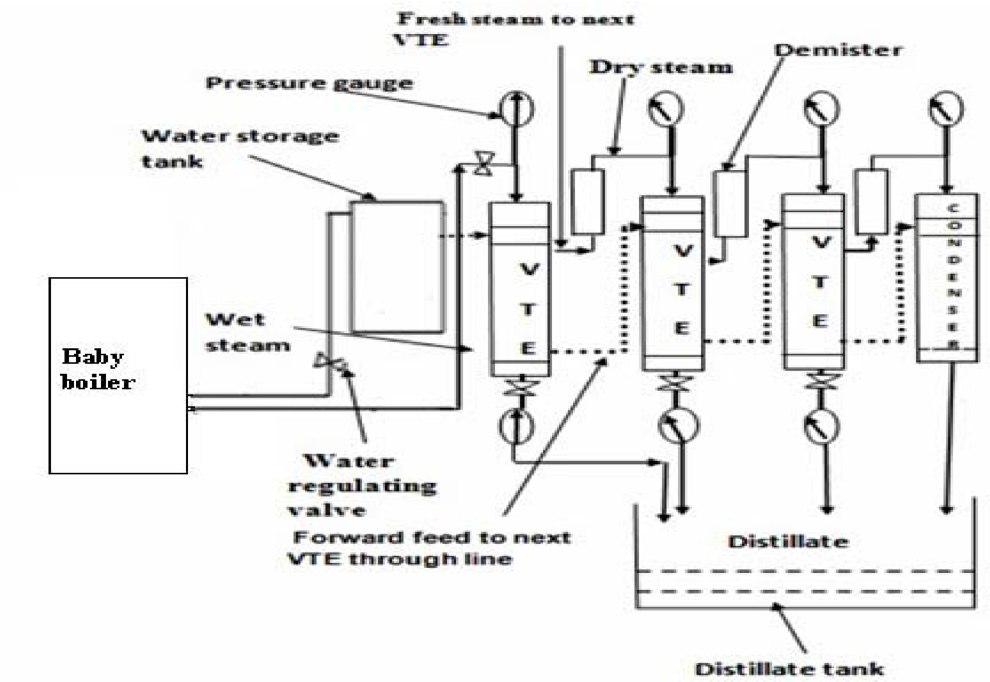

Fig. 1. Schematic diagram of Micro scale MED

2. Design and fabrication of MSMED system

The main components of the system as shown in Fig. 1, are vertical tube evaporators (VTEs), condenser, mist eliminators or feed entrainment separators, distillate withdrawal capillaries, forward feed and brine transferring capillaries, pump and other peripherals. The unit is insulated to minimize heat loss to the surroundings [1-2]. Primary steam from a baby boiler or a solar energy source is fed to the tube-side of the first VTE and this gets condensed by transferring its latent heat of condensation to the evaporating feed water on the shell-side. The fresh steam formed on the shell side of this VTE carries brine mist along with it. To remove the mist, it is passed through an inter-effect mist separator before being fed to the next effect and the process is repeated. Due to cyclonic effect heavier water particles settle down in the mist separator and steam moves upward due to lower density. The steam is further dewetted using de-mister screens. The steam generated in the last effect is condensed in a falling feed water film condenser. This liquid-film is actually the feed water (to be decontaminated) which is preheated in the process. The distillate and brine are withdrawn using capillaries, having diameters of 4.5 mm or less. The feed water progress is simplest if it passes from effect one to effect two, to effect three, and so on, as in these circumstances the feed will flow without pumping. This “forward feed” arrangement also helps in conservation of energy. Fresh brine from water storage tank is used for cooling the condenser and returned to the tank. In this way all vapours get condensed in the condenser. In our earlier work on a Small scale MED (SMED) each VTE had seven fluted aluminum tubes of calculated length and diameter designed for condensing ≈ 20 – 30 kg steam at 1.5 bar. Thus ≈ 3 – 5 kg steam condenses in each tube. Parametric studies were done for this system with 3 – 10 such VTE (effects) [3-5]. In the current study [6-7] on MSMED, only one fluted aluminum tube is used per VTE and three such effects are used with a condenser. As the dimension of the fluted tube was same as with SMED, in the VTE with one tube about 3 kg of steam can be condensed. In Fig. (2-4) the photographs of various fabricated components and assembly of MSMED are shown.

Fig.2. Unassembled parts of MED

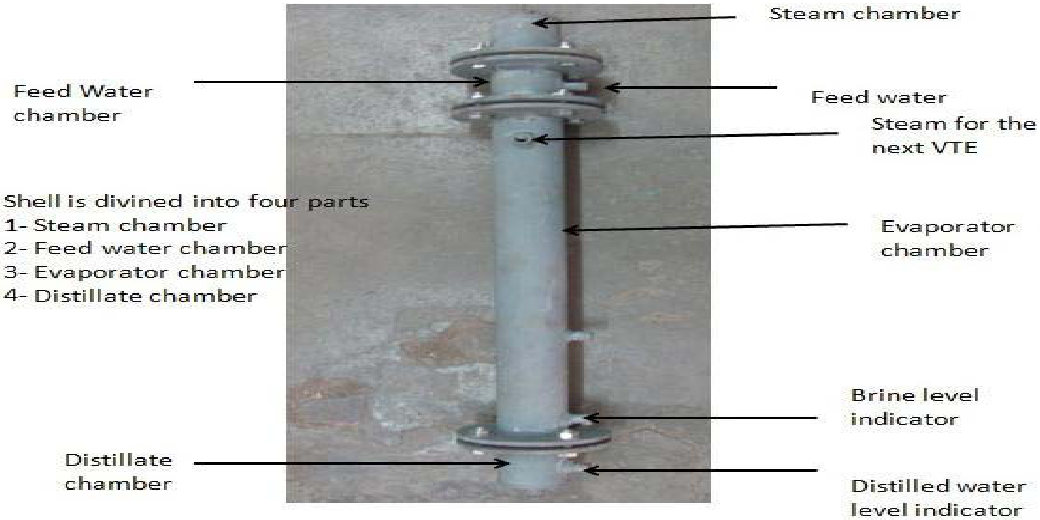

Fig. 3. Vertical tube evaporator

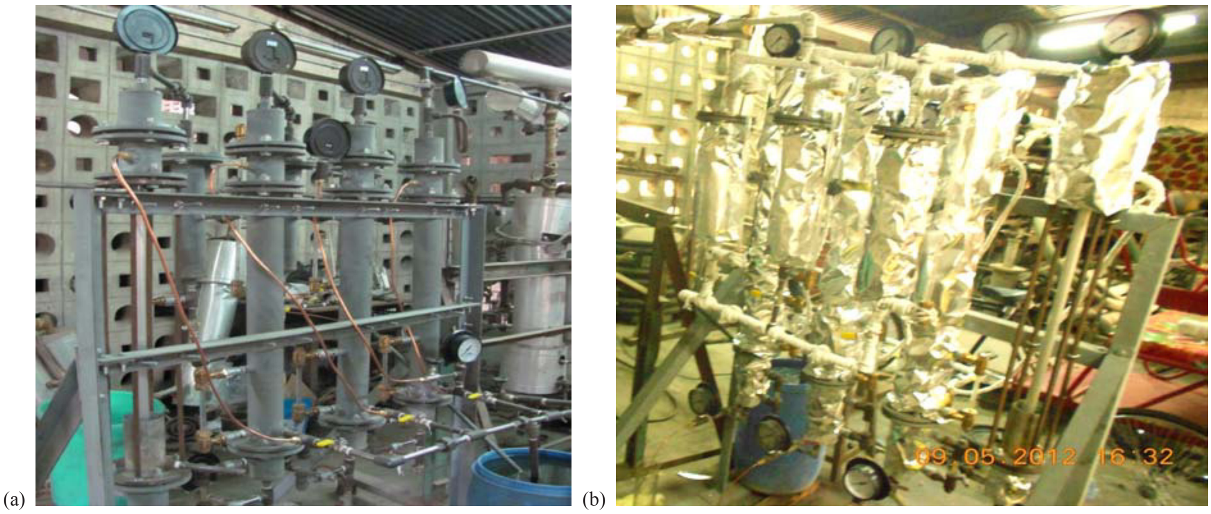

Fig.4. Micro scale multi effect distillation (MSMED) unit (a) before insulation (b) after insulation.

3. Calculations for operating conditions

3.1 Heat transfer area

The distillation process requires a large heat transfer area. The overall heat transfer coefficient U can be as high as 14,000 $W/m^2/K$ for a thin film vertical tube evaporator (VTE) using single fluted tubes. However, U=10,000 W/m^2-K was assumed in the present design, for readily available outside fluted 24 mm diameter aluminium tubes that are used in the construction of the VTEs. These tubes are commonly used as curtain rods. Further, considering the temperature difference, ΔT, across tube and shell sides of VTE as 5 °C (even though condensation of liquid for a heat transfer temperature difference of 2 °C has been reported), the heat transfer area is calculated using equation:

$M_d H_{fg} = UA\Delta T$

Assume H_{fg} = 2257 kJ/kg

U = 10000 W/M^2-K

ΔT = 5K

Here, M_d and H_{fg} are respectively the rate of condensation of steam, and latent heat of vaporization.

For a steam condensation rate (i.e., distillate flow rate) of 3 Kg/h, 0.0565 m^2 of heat transfer area is required for the values of ΔT and U assumed. Considering handling convenience and total height of VTE, a shell length of 0.75 m was needed to form the evaporator section of VTE. However, the actual tube length taken is 0.9 m; this account for projections outside tube plate and also the length of feed water jacket where feed water is sprayed. The value is close to that required for a temperature difference of 5 °C as assumed. There are 21 numbers of flutes in each tube, with flute depth of 0.50 mm, running along the length of the tubes. Fluting increases the actual area of heat transfer and also ensures very thin films at the ridges. This would allow for heat transfer for much smaller temperature differences between tube and shell side. For similarity in construction, the heat transfer area is kept identical in all VTEs, and also in the final condenser.

4. Experimental results

Analysis and investigations were done with the MSMED, (3 effects + Condenser). The unit was operated with input primary steam pressure supplied by a baby boiler in the range of 1.2 bar gauge to 1.6 bar gauge with increment of input steam pressure of 0.2 bar. All the readings namely pressure, temperature and distillate production were measured and recorded at different locations for each input steam pressure. The sum of distilled water produced from each effect, or cumulative distillate production, at a given input steam pressure, is the indicator of plant performance. At each input pressure the whole set of readings were repeated four times and the average figures obtained.

In table 1 the amount of distillate, D1 – D3 in the three effects and D4 in the condenser, and total cumulative distillate D, are shown, for the insulated system. It is seen that inlet pressure of 1.4 bar gives optimal distillate output. Table 2 shows the recovery ratio at each effect for different steam input pressures. It was also seen that the heat transfer is high and optimal at 1.4 bar input pressures, and, the overall heat transfer coefficient (OHTC) was found to be in the range of 6000-7000 W/M^2-K. This is less than the figures obtained in Sen et al. [3-5], because the feed water was not pre-heated, and part of the evaporator tube length was used up in raising the feed water temperature to saturation.

Table 1. Distilled water flow rate at different inlet steam pressures

distilled water flow rate	D1(kg/h)	D2(kg/h)	D3(kg/h)	D4(kg/h)	$D=\sum_1^4 D_i$	GOR (D/D1)
inlet pressure 1.2 bar gauge	3	2.85	2.55	2.4	10.8	3.6
inlet pressure 1.4 bar gauge	3.1	2.96	2.72	2.69	11.47	3.7
inlet pressure 1.6 bar gauge	3.15	2.96	2.66	2.55	11.32	3.59

Table 2. Recovery ratio at different inlet steam pressures

Recovery ratio	D2/D1	D3/D2	D4/D3
inlet pressure 1.2 bar gauge	0.95	0.89	0.94
inlet pressure 1.4 bar gauge	0.995	0.92	0.98
inlet pressure 1.6 bar gauge	0.94	0.90	0.96

5. Conclusion

An efficient MSMED system for rural communities has been designed, fabricated and optimized. As for rural application, where decentralized production and supply of water is needed, the plant should be small, cost effective and easy to construct, operate and maintain. Overall features and conclusions drawn are summarized below:

1) The unit designed and fabricated is rugged and robust and can easily be installed and operated in rural circumstances by rural populations with a little training.
2) The unit is capable of producing 80 to 90 liters distilled water per day, for about 7 hrs of operation.
3) Very high overall heat transfer coefficients (OHTCs) were obtained i.e. in the range of 6,000 – 7000 W/m^2-K, due to simultaneous phase change on both sides of the heat exchanger tubes, viz. condensation of steam in the tube side, and evaporation of feed water in the shell side.
4) On increasing the input steam pressure, the quantity of distillated water increases and reaches a maximum value at the respective optimum pressure of 1.4 bar gauge for 3 effects + Condenser.
5) At the inlet steam pressure of 1.4 bar gauge the Gained Output Ratio is 3.7. This indicates effective utilization of energy.
6) The system has reduced TDS from initial value of 748 ppm to 7 ppm. The performance depends on quality of feed water and proper functioning of VTEs and demisters. From the output results obtained we can say that fabricated VTEs and demisters are working well as the quality of distilled water depends on the demister. The minimum recorded TDS value of distilled water was 7 ppm and maximum was 9 ppm.
7) If steam is raised using solar energy there will be considerable saving of energy, since the main energy input is for raising the primary steam in the baby boiler.

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